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Estimating the Weight of Crown Segments for Old-Growth Douglas-Fir and Western Hemlock

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Abstract

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Equations were developed for predicting weight of continuous live crown, total live crown, dead crown, any segment of live crown, and individual branches for old-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) trees. A branch method and a ratio method were developed for estimating the weight of crown segments. Equations were based on data from 32 Douglas-fir and 29 western hemlock trees from the Gifford Pinchot National Forest in southwestern Washington. An additional 49 Douglas-fir and 50 western hemlock were selected for validating the models.

For predicting weight of a segment of crown, the branch method was less biased and more accurate than the ratio method. The branch method is recommended for felled trees because it more easily accommodates the large amount of breakage in the crown of felled old-growth trees.

Keywords: Crown weights, estimates, moisture content (wood), old-growth stands, Douglas-fir, western hemlock.

Summary

The purpose of this study was to develop and validate estimators to predict total crown weight and weight of any segment of crown for old-growth felled and bucked Douglas-fir and western hemlock trees. Equations were developed for predicting weight of continuous live crown, total live crown, dead crown, any segment of live crown, and individual branches. A branch method and ratio method were developed for estimating the weight of crown segments. Equations were based on data from 32 Douglas-fir and 29 western hemlock trees from the Gifford Pinchot National Forest in southwestern Washington. An additional 49 Douglas-fir and 50 western hemlock were selected for validating the models.

For predicting weight of a segment of crown, the branch method was less biased and more accurate than the ratio method. The branch method is recommended for felled trees because it more easily accommodates the large amount of breakage in the crown of felled old-growth trees.

Variation in the amount of crown broken off during felling is a major practical problem in estimating the weight of crown that remains attached to logs or felled trees. The weight of crown remaining attached to old-growth Douglas-fir trees after felling ranged from 1 to 59 percent. (Crown breakage was not measured for western hemlock.)

Contents

Introduction

Airborne and cable logging systems for yarding large trees in the west require large capital investments, and efficient, effective, and economical operation of these systems is critical. Further, more expensive, heavy-lift airborne logging systems are being developed; for example, the Heli-Stat (Piasecki Aircraft Corporation under contract with the USDA Forest Service and the U.S. Navy) and the Cyclo-Crane (AeroLift Inc.).[1/] These new systems use lighter-than-air dirigibles to support the craft, motors, and wings that in turn provide thrust for lifting. For these logging systems or any other high-cost aerial logging system (such as helicopters) to operate efficiently, the weight of each payload must be as close to optimum as possible.

Because trees and logs cannot be weighed conveniently prior to hookup and transport, a method is needed to accurately estimate their weight after being felled and bucked. In the interest of logging residue cleanup and utilization, sometimes the crowns of trees are removed during yarding. Many models have been developed for predicting weight of crowns of western tree species (for example, Adamovich 1970, Brown 1978, Fujimori 1971, Fujimori and others 1976, Gholz and others 1979, Snell and Anholt 1981, Woodard 1974). These and other studies, however, do not provide prediction equations for weight of any segment of the continuous crown for old-growth trees between 14 and 157 cm in diameter at breast height (dbh). When trees are felled and bucked, the amount of crown on any one log will depend on at least two major factors: (1) location of the log in the tree relative to the crown, and (2) the amount of crown physically removed by felling the tree. Accurate weight estimates for both crown and bole may be required to achieve acceptable payloads when crowns are yarded with logs.

The objectives of this study were to develop and validate estimators to predict the total crown weight, as well as the weight of any segment of crown for old-growth felled and bucked Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) trees. For clarity, the developmental part of the study is referred to as MODEL BUILDING and the validation part as MODEL VALIDATION.

[1/] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U. S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

Population

The population for MODEL BUILDING was all qualifying Douglas-fir and western hemlock trees on three 2-ha areas in the Wind River Experimental Forest, Gifford Pinchot National Forest, Washington. Trees sampled were over 200 years old and their dbh ranged from 14 to 157 cm (table 1).

Some trees in the sample areas were excluded from the population if they had (1) sufficient decay in the upper merchantable bole to produce a spiked top, (2) excessive lean, (3) crown damage due to logging, (4) a forked merchantable bole, or (5) heavy mistletoe infection. These trees were excluded because they were not safe to sample (see Measurements section and fig. 1) and with excessive rot the upper bole would probably shatter during felling, making it impossible to yard the crown with the bole.

The population for MODEL VALIDATION was all qualifying Douglas-fir and western hemlock trees on a separate 8.1-ha stand in the Wind River Experimental Forest. Trees were excluded using the same criteria as for the population for MODEL BUILDING, except trees with excessive lean were not excluded as they did not have to be climbed for the validation part of the study.

Table 1—The frequency distribution of diameter at breast height (dbh) for the sample trees in the study area, Wind River Experimental Forest, Washington

	MODEL BUILDING		MODEL VALIDATION	
Dbh class	Douglas-fir	Western hemlock	Douglas-fir	Western hemlock
Centimeters				
10	—	—	—	1
20	—	—	—	2
30	—	2	1	2
40	—	2	2	7
50	—	4	5	5
60	2	5	1	4
70	3	3	6	5
80	2	3	5	5
90	4	6	4	6
100	3	2	11	2
110	3	2	3	5
120	3	—	4	4
130	4	—	6	1
140	2	—	1	1
150	5	—	—	—
160	1	—	—	—
Total	32	29	49	50

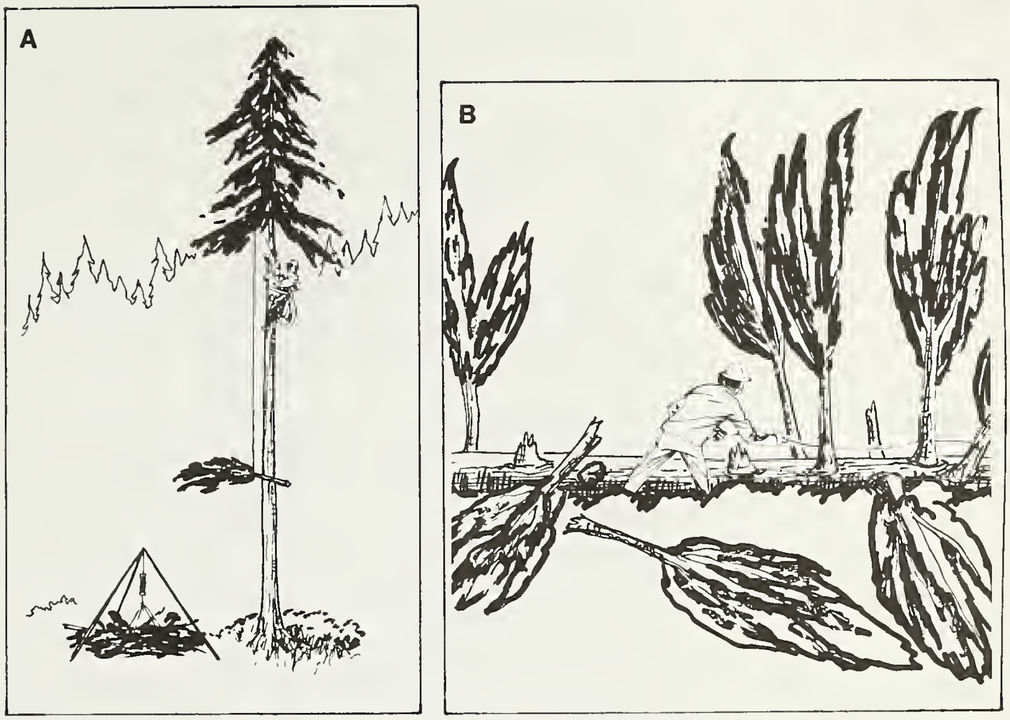

Figure 1.—Two data collection procedures were used in the study: (A) Trees were climbed and branches were carefully lowered when data were collected for MODEL BUILDING; (B) trees were felled and crown remaining after felling was measured for MODEL VALIDATION (note that breakage occurred during felling).

Methods

The two parts of this study, MODEL BUILDING and MODEL VALIDATION, used quite different approaches. Data for MODEL BUILDING were obtained by carefully removing each branch in the crown of sample trees while the trees were standing (fig. 1a). Branches were carefully dropped or lowered to the ground to accurately measure branch and crown weight. On the other hand, data for MODEL VALIDATION were collected under conditions similar to logging operations (fig. 1b) to test the applicability of the models in a realistic application. Trees were felled and models from the MODEL BUILDING phase were used to predict weights of segments of crowns to compare to the actual measured weights of these segments.

Sampling

Trees

For building the models, trees were selected from the population defined for MODEL BUILDING. All qualifying Douglas-fir and western hemlock trees were stratified by species and dbh; 32 Douglas-fir and 29 western hemlock were selected. Trees of each species were randomly selected within dbh classes, but the sample was distributed among dbh classes to obtain more of the larger trees. The diameter distribution of the trees in the MODEL BUILDING sample is given in table 1.

For validation of the models, a similar stratified sample was obtained from the population defined for MODEL VALIDATION; 49 Douglas-fir and 50 western hemlock were selected uniformly across the diameter classes. The diameter distribution of the trees in the MODEL VALIDATION sample is given in table 1.

Branches

Four sample branches were selected from each sample tree in the data set for MODEL BUILDING. These branches were needed to develop a prediction equation for branch weight from branch basal diameter and to estimate the proportions of branch weight in various classes of material; for example, needles and branch wood diameter classes 0-0.5 cm, 0.6-2.5 cm, etc. The four sample branches were selected as follows. The total number of branches and the maximum diameter of branches were estimated for each tree based on visual observations. The basal diameter range of branches was stratified into four diameter classes and the number of branches in each class was estimated. A random number was selected for each class that was less than the estimated maximum number of branches for that class. These random numbers were used to select one sample branch from each of the four diameter classes.

Four sample branches were also selected from each sample tree in the data set for MODEL VALIDATION. These branches were used to validate the prediction equations developed from the data set for MODEL BUILDING. One branch from each of the following diameter classes was selected from each tree:

Class	Range of basal diameter
	(Centimeters)
1	Less than 0.5
2	0.5 to 2.5
3	2.6 to 5.5
4	Greater than 5.5

Crown Sections

For MODEL BUILDING, the crown was separated into a maximum of 10 horizontal strata. The first strata was that portion below the continuous crown. The second to the tenth strata were in the continuous crown. Continuous crown is that part of the crown above where the internodal distance becomes regular and is less than 1.8 m and branches occur on at least three sides of the tree (fig. 2). Total crown includes the continuous crown plus all other live branches below the continuous crown. The length of these crown strata (sections) in the continuous crown varied, depending on internodal distances and the number of branches at each whorl. We tried to obtain a minimum of 10 to 12 branches and a crown section length of approximately 4 m. The number of sections ranged from 2 to the maximum of 10.

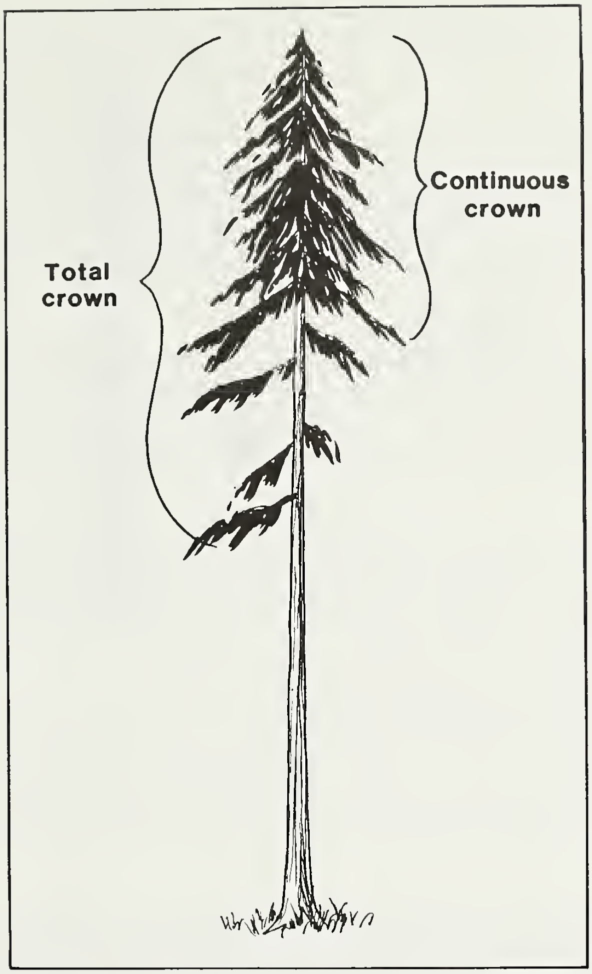

Figure 2.—Continuous crown is that part of the total crown above where the internodal distance becomes regular and is less than 1.8 m and branches occur on at least three sides of the tree.

For trees in the MODEL VALIDATION data set, only one section of crown was selected to be measured and used for validation. The sample crown section was restricted to be entirely within the continuous crown and not extend into the upper 10 percent of the continuous crown. For each species, the crown section was selected from the top one-half of the crown for one-half of the trees and from the bottom one-half of the crown for the other one-half of the trees. Assignment of top or bottom one-half was systematic. The actual location of the sample crown section was selected randomly within the top or bottom one-half of the crown. The length of the sample crown section was 4.6, 7.6, or 10.7 m depending on the length of the continuous crown in the sample trees; the longer the continuous crown the longer the sample section. Length of the sample section was restricted to be less than or equal to 50 percent of the continuous crown length.

Measurements

Field

Small trees, shrubs, logs, and litter were cleared from the base as far out as crown diameter for trees in the MODEL BUILDING data set. Dbh, crown width, height to base of the live continuous crown, and total height were recorded.

A tree climber climbed the tree and measured the minimum branch basal diameter of each branch before sawing it from the bole (fig. 3). After removal, all limbs were grouped by crown section except that all dead limbs were grouped together. Each group of limbs, either a crown section or all dead limbs, was weighed in the field using a spring scale, and moisture samples were taken from each branch component.[2]

The four sample branches in each tree were treated separately from the other branches. These sample branches were carefully lowered to the ground to prevent shattering and loss of material. They were physically separated into branch components and a moisture sample taken for each component.

For trees in the MODEL VALIDATION data set, basic tree measurements taken were dbh, total height, and height to base of continuous crown. The tree was then felled and a series of measurements were taken on the sample section of crown selected for validating the models. These measurements were:

1. Minimum basal diameter of all branches.
2. Estimated percentage of live branch weight lost because of breakage for whole crown and sample crown section.
3. Height from base of continuous crown to bottom of sample crown section.
4. Length of sample crown section.
5. Weight of all branches for which basal diameters were recorded.
6. Average percentage of moisture in crown section.

After the tree was felled, all live branches were removed from the sample crown section, chipped onto a tarp, and weighed to obtain green weight. Because the prediction models estimate dry weight, moisture content was determined for the section to compute actual dry weight. Two samples of the chipped material were selected to estimate moisture content for the section. Each sample was approximately 1 kg and contained a good mixture of foliage and wood from all sizes of branches.

Because the chipper could only chip material up to 10.2 cm in diameter, all branch material larger than 7.6 cm was weighed separately from the rest of the crown. Thin disks were cut from this material and placed in two airtight containers to obtain moisture content. The average moisture content from these samples was used to estimate dry weight of the crown section from green weight for this larger material.

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[2] Components are defined as follows: foliage and branch wood 0 to 0.5, 0.6 to 2.5, 2.6 to 7.5, and 7.6 cm and larger in diameter.

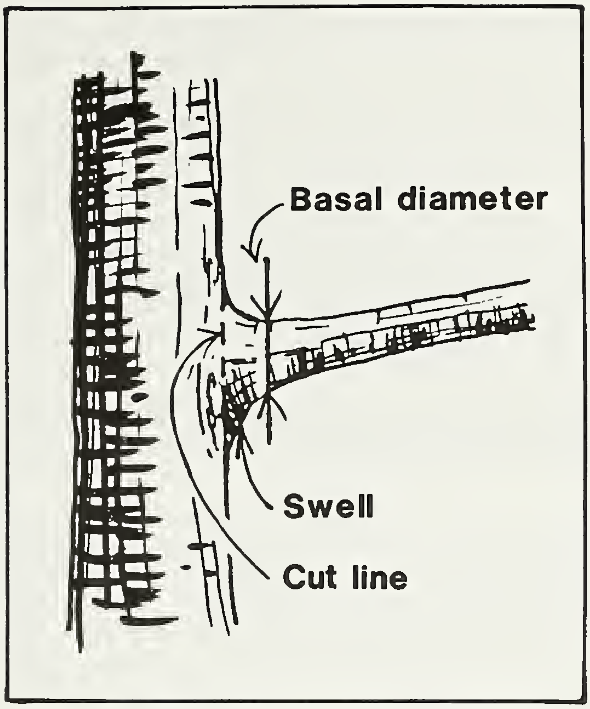

Figure 3.—Minimum branch basal diameter was measured outside swelling that occurs at the base of the branch.

Four sample branches from each tree were individually measured for minimum basal diameter, green weight, and moisture content. Dry weight was determined from green weight and moisture content. Moisture content was the average of two samples.

Laboratory

Green and dry weights were measured on all moisture samples to determine moisture content. For MODEL BUILDING, woody material larger than 0.6 cm in diameter was ovendried at 102 °C for a minimum of 15 hours (Ponto 1972). Foliage and woody material smaller than 0.6 cm in diameter were ovendried at 70 °C for a minimum of 15 hours. Foliage and the smaller branchwood were dried at the lower temperature to reduce the loss of volatiles. For MODEL VALIDATION, all chips were dried at 102 °C.

Determining Dry Weight

For the MODEL BUILDING data, an appropriate moisture content was needed to convert crown section green weight to ovendry weight because all analyses were done on ovendry weights. Other investigators (for example, Brown 1978) have reported that moisture content varies from bottom to top of crown as well as by size of material within the crown. We sampled foliage and four branchwood size classes (see footnote 2) and crown sections up the tree for moisture content. Table 2 gives the average moisture contents for foliage and branchwood size classes by species. We also determined the proportion, by weight, of these components based on their branch basal diameters. From this information, a composite moisture content was computed for converting green crown weight to ovendry weight. Ovendry weight was then used to develop regression equations for total continuous crown weight.

Table 2—Average moisture for foliage and branch wood of Douglas-fir and western hemlock by size class

Species and branch component	Number of samples	Average moisture content	Standard error of the mean
		Percent	Percent
Douglas-fir:			
Foliage	117	100	1.2
Branch wood—			
0 to 0.5 cm	117	82	.9
0.6 to 2.5 cm	117	83	.8
2.6 to 7.5 cm	117	71	1.0
7.6+ cm	69	56	1.2
Western hemlock:			
Foliage	130	105	2.2
Branch wood—			
0.0 to 0.5 cm	130	77	1.1
0.6 to 2.5 cm	130	82	.8
2.6 to 7.5 cm	127	73	1.0
7.6+ cm	53	58	1.7

The composite moisture percent was calculated as follows:

1. The ovendry weights of sample branch components (leaves and branchwood diameter classes) were calculated using moisture samples collected from these components.
2. These weights were regressed separately on their branch basal diameters.
3. These regression equations were then used to estimate the weight of each component for every branch on each tree.
4. The weight of each component was summed for all branches within each crown section.
5. These component total weights for each section were used as weighting factors to estimate a composite moisture content for the section.

These composite moisture percentages were then used to convert the green crown section weight to estimates of ovendry weight. A similar procedure was used by Brown (1978) and suggested by Ek (1979).

Because all of the dead branch wood was separated into diameter classes, the moisture samples taken from each class were used to convert them to ovendry weight.

For the MODEL VALIDATION sample, composite 1-kg samples were selected from the chipped material, and sample disks were selected from branch parts larger than 7.6 cm. Two samples of each type of material were selected from each sample crown section and each sample branch. Moisture content was computed for each composite sample and group of sample disks as described above. The average of the two moisture contents was used to convert green weight to dry weight. Conversions were computed separately for the chipped material and branch wood larger than 7.6 cm.

Model Development

Three different approaches were tried for modeling weight of any segment of crown. The methods are the branch method, ratio method, and bole section method. These methods required development of prediction equations for weight of the continuous crown and individual branches. In addition, equations were developed for predicting weight of total live crown and dead crown.

Branch Method

The branch method uses a prediction equation to estimate weight of individual branches from their minimum basal diameter (Brown 1978, Ek 1979). Estimated weight of a crown segment is the sum of the estimated weight of all the branches in that crown segment.

There are several disadvantages to this method. The most important is the lack of compatibility between the estimated weight of segments and the estimated weight of the whole crown. These models are compatible if the sum of the estimated weights for all the segments of the crown equals the weight of the whole crown estimated by the model predicting whole crown weight. Using this method the combined weights of all crown segments does not equal the total crown weight, even though the crown segments completely subdivide the crown. A further disadvantage is that every branch basal diameter in the section must be measured or estimated. An advantage of the method is ease in adjusting for branches or parts of branches broken off during felling. Branches that are completely broken off are simply not measured. For partial branches the predicted weight is reduced using an estimate of the percent missing.

Ratio Method

The ratio method is based on two regression equations. The first predicts total continuous crown weight and the second predicts a ratio of weights. Ratios and lengths are illustrated in figure 4. The dependent variable is the ratio of crown weight between the bottom of the live continuous crown and any particular point in the crown to total continuous crown weight. The independent variable is ratio of length of the same lower crown section, beginning at the bottom of the live continuous crown, to total continuous crown length. The model is restricted so the dependent variable ranges between zero and one. The weight ratio for any crown segment not beginning at the base of the crown is determined by the difference in two ratios. The first weight ratio is for the part of the crown from the base of the continuous crown to the base of the crown section. The second ratio includes the part of the crown in the first ratio plus the crown section. The difference in these two ratios is the weight ratio for the section. The weight of this section is estimated by multiplying the estimated weight ratio by the total continuous crown weight. This approach is similar to volume ratio models developed to estimate volume of tree boles to any top diameter (Burkhart 1977, Cao and others 1980).

The advantage of this method is the compatibility of the resulting estimates. The ratio for the whole continuous crown is one, so the weight of the whole continuous crown is determined by the equation for predicting the whole continuous crown weight. The segments of the continuous crown completely subdivide the continuous crown so the sum of all the weight ratios for the segments is one. The sum of weights for all segments therefore equals the weight of the whole continuous crown.

The main disadvantage of this method is the measurements required. These measurements include total continuous crown length, length from the base of the continuous crown to the base of the crown section, and length of the crown section. These measurements are difficult to obtain in an operational environment.

Bole Section Method

The bole section method relates the weight of the crown segment to characteristics of the section of bole to which it is attached. Candidate independent variables were diameter of the small and large end of the bole section, diameters of the bole where the crown began and ended, and length of the crown segment. This method, like the branch method, is not compatible. The advantage of the bole section method is the simplicity of required measurements. Only log diameters and lengths are needed.

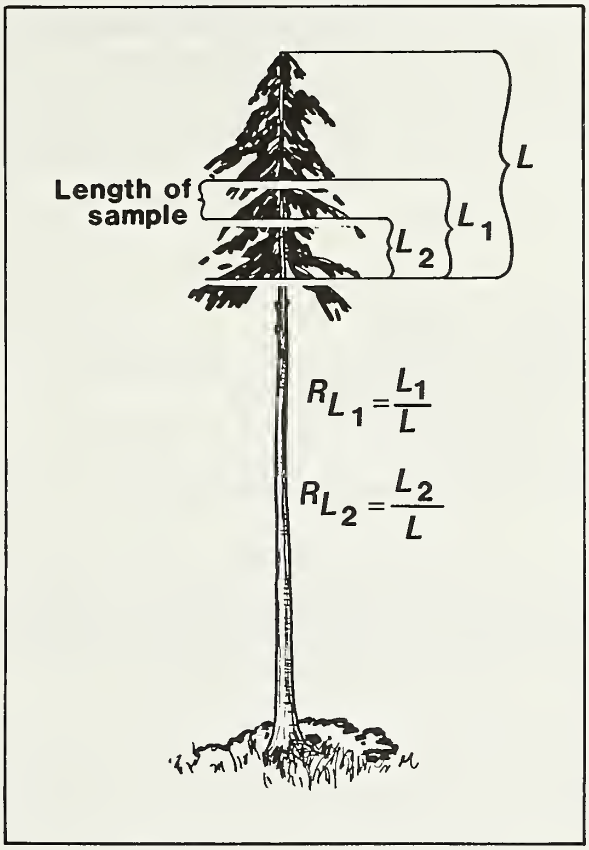

Figure 4.—Lengths of the parts of the crown used in the ratio method. *L* is the length of the continuous crown. Crown below the continuous crown has been removed. *L*2 is the length of the crown below the sample section. *L*1 is the length from the bottom of the live crown to the top of the sample section. Length of the sample section is *L*1 minus *L*2.

Model Estimation

Branch Method

The branch method is based on a regression equation for predicting weight of individual branches. The equations were developed from the MODEL BUILDING data. Several models were considered involving transformations of variables and slightly different equation forms. Selection of the final model was based on the coefficient of determination (R^2), standard error about regression ($s_{y.x}$), residual plots, and the desirability of having a common model for both species. The model selected was

$$\ln \hat{w}_B = A + B \ln(d);$$

where:

$\ln$ = natural logarithm,
$\hat{w}_B$ = estimated ovendry branch weight (kg),
A,B = regression coefficients, and
d = minimum basal diameter of branch (cm).

The results are summarized in table 3.

The validation data provided an opportunity to test the predictive ability of the equations for estimating weight of individual branches. Validation of the branch method for estimating weight of segments of crowns is described in the VALIDATION section. The following paragraph describes validation of just the equations for predicting weights of individual branches.

Data from MODEL VALIDATION sampling were used to validate the equations for predicting weight of individual branches. For each branch in the validation data the difference between the actual and predicted dry weight was computed. These differences were used to estimate bias and accuracy of the equations (table 4). Plots of these differences against branch diameter revealed that prediction error increased with branch diameter for both species. The equations for both species had relatively little bias.

Table 3—Regression equations for predicting ovendry weight of Douglas-fir and western hemlock branches

$$\ln \hat{w}_B = A + B \ln (d)$$ [1]

Species	A	B	Number of samples	Mean square error	R^2
Douglas-fir	–2.7552	2.2150	128	0.15	0.96
Western hemlock	–2.6895	2.3254	116	.21	.96

[1] ln = natural logarithm, $\hat{w}_B$ = estimated branch ovendry weight in kilograms, A and B = regression coefficients, and d = branch basal diameter in centimeters.

Table 4—Predictive ability of the regression equations for predicting branch weight as determined from the MODEL VALIDATION data

Species	Bias[1]	Mean absolute difference[2]	Root mean squared difference[3]
	Kilograms		
Douglas-fir	–0.06	0.27	0.62
Western hemlock	.02	.78	1.80

[1] Bias = $\sum_{i=1}^{n} (w_{Bi} - \hat{w}_{Bi})/n$;

where: n = number of branches,
w_{Bi} = observed weight of i^{th} branch, and
$\hat{w}_{Bi}$ = predicted weight of i^{th} branch.

[2] Mean absolute difference = $\sum_{i=1}^{n} |w_{Bi} - \hat{w}_{Bi}|/n$.

[3] Root mean squared difference = $\left[\sum_{i=1}^{n} (w_{Bi} - \hat{w}_{Bi})^2/n\right]^{1/2}$.

Ratio Method

The ratio method used the MODEL BUILDING data to develop two prediction equations. One equation predicts total continuous crown weight. The other equation predicts a weight ratio; that is, the proportion of weight in any segment of crown.

For total continuous crown weight, candidate models were those proposed by other researchers (for example, Brown 1978, Gholz and others 1979, Schlaegel 1975). Only models that used dbh as the independent variable were considered. The final model was selected using the same criteria as in the branch method.

The model selected for total live continuous crown weight was

$$\ln \hat{w}_L = A + B\ (\text{dbh});$$

where:

ln = natural logarithm,
$\hat{w}_L$ = estimated ovendry weight of the live, continuous crown (kg),
A, B = regression coefficients, and
dbh = diameter at breast height (cm).

These results are summarized in table 5.

Weight ratios were plotted against the length ratios and variation seemed reasonably homogeneous, except near zero and one, where it approached zero. Several models were tried to relate weight ratio to length ratio. The models tried were similar to models used for volume ratios (Cao and others 1980). The final model was selected using similar criteria as for other models and was

$$\hat{R}_w = \exp\ (A\ (1 - R_L)^B);$$

where:

$\hat{R}_w$ = estimated ratio of crown segment weight to total continuous crown weight,
exp() = the base of natural logarithms (e) raised to the power in parentheses,
A, B = regression coefficients, and
R_L = ratio of crown segment length to total continuous crown length.

Nonlinear regression was used to fit this model and results are summarized in table 6.

Table 5—Regression equations for predicting ovendry weight of live continuous crown of Douglas-fir and western hemlock

$$\ln \hat{w}_L = A + B\ (\text{dbh})^{1/}$$

Species	A	B	Number of samples	Mean square error	R^2
Douglas-fir	3.9436	0.0203	32	0.16	0.71
Western hemlock	3.7943	.0341	29	.15	.80

1/ ln = natural logarithm, $\hat{w}_L$ = estimated ovendry weight of live continuous crown in kilograms, A and B = regression coefficients, and dbh = diameter at breast height in centimeters.

Table 6—Regression equations for predicting weight ratio from length ratio for Douglas-fir and western hemlock crowns

$$\hat{R}_w = \exp(A\ (1-R_L)^B)^{1/}$$

Species	A	B	Number of samples	Mean square error
Douglas-fir	-3.5703	2.3831	125	0.0079
Western hemlock	-3.0364	2.2964	164	.0077

1/ $\hat{R}_w$ = estimated weight ratio, crown section ovendry weight over total continuous crown ovendry weight, exp = the base of natural logarithms (e) raised to the power in parenthesis, A and B = regression coefficients, and R_L = length ratio, crown section length over total continuous crown length.

Bole Section Method

In the bole section method, the weight of crown attached to a section of bole was related to measured characteristics of the section. There were no strong relationships found and the bole section method was dropped from further consideration.

In addition to the models built for the branch and ratio methods, equations were also developed for total live and dead crown weight. The model selected for total live crown weight was

$$\ln \hat{w}_T = A + B\ (\text{dbh});$$

where:

ln = natural logarithm,
$\hat{w}_T$ = estimated total live crown weight (kg),
A,B = regression coefficients, and
dbh = diameter at breast height (cm).

A slightly different model was selected for total dead crown weight:

$$\ln \hat{w}_D = A + B \ln (\text{dbh});$$

where:

$\hat{w}_D$ = estimated total dead crown weight (kg) and other symbols are the same.

These regression models are summarized in table 7.

Table 7—Regression equations for predicting ovendry weight of total live crown and dead crown for Douglas-fir and western hemlock

Live or dead crown and species	A	B	Number of samples	Mean square error	R^2
Live crown:					
	$\ln \hat{w}_T = A + B\,(\text{dbh})$[1]				
Douglas-fir	4.0068	0.0206	32	0.14	0.73
Western hemlock	3.8886	.0338	29	.13	.82
Dead crown:					
	$\ln \hat{w}_D = A + B \ln (\text{dbh})$[1]				
Douglas-fir	-10.6294	3.2692	32	.25	.79
Western hemlock	-5.4241	2.2577	29	.24	.73

[1] ln = natural logarithm, $\hat{w}_T$ = estimated ovendry weight of live total crown in kilograms, A and B = regression coefficients, dbh = diameter at breast height in centimeters, and $\hat{w}_D$ = estimated ovendry weight of dead crown in kilograms.

Model Validation

The VALIDATION DATA were obtained to provide independent estimates of bias and average prediction error for the branch and ratio methods. Each observation was the weight (w_i) of one section from each tree in the sample. The dry weights of these sections were predicted using both the branch and ratio methods. Differences were computed between the observed and predicted section weights using both methods of prediction. Bias and accuracy were estimated from these differences for each species (table 8).

The branch method is substantially less biased and more accurate than the ratio method for both species for this independent data set (table 8). This is not surprising as the branch method uses the diameters of all branches in the sample crown section, substantially more information about the particular crown section than is used in the ratio method.

The ratio method was substantially more biased and, therefore, less accurate for western hemlock than for Douglas-fir. Examination of the data revealed that much of this inaccuracy was caused by poor predictions of total continuous crown weight in large western hemlock trees. In the MODEL BUILDING data for western hemlock the largest dbh was 111.6 cm, and only three trees had a dbh larger than 100 cm. The slope of the prediction curve increased rapidly for a dbh larger than 100 cm. The MODEL VALIDATION data set contained 11 trees with diameters at breast height between 105 cm to 143 cm. The prediction equation appeared to substantially overestimate weight of total continuous crown for these trees. The results shown in parentheses in table 8 are with these 11 trees eliminated. Although eliminating these trees reduced bias and increased accuracy somewhat, the ratio method still did not compare favorably to the branch method. Because of the apparent inaccuracy in estimating total continuous crown weight for large diameter old-growth western hemlock trees, this method is not recommended for western hemlock with a dbh greater than about 100 cm.

Discussion

The trees in this study represented a very limited scope in sampling. The MODEL BUILDING data were from three small areas and the MODEL VALIDATION data were from one somewhat larger area nearby. Results are only strictly applicable to these sampled populations. We believe, however, that the results of this study are applicable to trees similar in age and size, and grown under similar conditions, at least in the Wind River Experimental Forest and in the Gifford Pinchot National Forest. Results could probably be applied with caution on a wider basis.

The amount of crown broken off during felling is a major practical problem in estimating the weight of crown that remains attached to logs or felled trees. Amount of crown broken off during felling was measured in our validation sample of old-growth Douglas-fir. In this case, an average of only 10 percent of total crown weight remained attached after the trees were felled. The range was from 1 to 59 percent. This large amount of breakage and the variation from tree to tree eliminates application of estimates from standing trees to felled trees. In many cases the weight of attached crown will be negligible relative to log or bole weight. The drag on lifting logs with pieces of crown attached could be affected more by limbs being pinned beneath other logs or trees than by the weight of the crown itself. Breakage of crowns was not measured for old-growth western hemlock but visual observations indicated it was less than for Douglas-fir but still substantial. We recommend using the branch method for predicting weight of crown attached to felled, old-growth trees because it more easily accommodates the large amount of breakage.

Table 8—Bias and accuracy of branch and ratio methods determined from MODEL VALIDATION data

Species and method	Bias[1]	Mean absolute difference[2]	Root mean squared difference[3]
	Kilograms		
Douglas-fir:			
Branch	-3.5	6.6	10.3
Ratio	-13.3	21.0	28.5
Western hemlock:			
Branch	-4.2	15.8	25.2
Ratio[4]	-88.6	93.7	152.1
	(-37.6)	(44.1)	(67.0)

[1] Bias $= \sum_{i=1}^{n} (w_i - \hat{w}_i)/n$;

where: n = number of sample crown sections,
w_i = observed weight of sample crown section, and
$\hat{w}_i$ = predicted weight of sample crown section.

[2] Mean absolute difference $= \sum_{i=1}^{n} |w_i - \hat{w}_i|/n$.

[3] Root mean squared difference $= \left[\sum_{i=1}^{n} (w_i - \hat{w}_i)^2/n \right]^{1/2}$.

[4] Values in parentheses are for the ratio method after 11 western hemlock with dbh larger than 108 cm were eliminated.

Example

An example is given illustrating the use of the developed prediction equations. Equivalent English measurements are given in parenthesis throughout this example. Suppose a 100-cm (39-in) Douglas-fir tree is felled and bucked, and one of the logs to be yarded has 10 m (32.8 ft) of continuous crown.

Application of the branch method is straightforward. The basal diameter of each branch attached to the log after felling is measured and used to predict the dry weight of the branch (fig. 5). The prediction equations used are given in table 3. Total weight of the crown section is the sum of the predicted weight of all the branches. This total weight is ovendry weight, which must be converted to green weight. Because moisture percent can change between areas, trees in the immediate area should be sampled to determine an applicable moisture percent.

For the ratio method the example is as follows: Before felling the 100-cm (39-in) Douglas-fir tree, the continuous crown length is measured at 30 m (98 ft). From measuring the tree on the ground, it is determined that the 10-m (32.8-ft) crown section to be yarded with the log is 7 m (23 ft) up the bole from the base of the continuous crown (fig. 6).

Total weight of the continuous crown is estimated using the equation for Douglas-fir in table 5. For dbh 100 cm (39 in), the estimate of total weight of the continuous crown is 393 kg (867 lb). To determine the weight of the 10-m (32.8-ft) crown section, two weights must be estimated. These two weights are the weight of the lower 7 m (23 ft) of continuous crown and the weight of the lower 17 m (56 ft) of continuous crown. Note the 17-m (56-ft) section consists of the 10-m (23-ft) section of interest plus the 7-m (23-ft) of continuous crown below this section. The difference between the weights of the 17-m (56-ft) section and the 7-m (23-ft) section is the estimated weight of the 10-m (32.8-ft) crown section of interest.

The computations are as follows. The first weight ratio is computed using a length ratio of 7/30 = 0.23 (that is, $R_L = 0.23$). Substituting $R_L = 0.23$ into the equation in table 6 for Douglas-fir results in an estimated weight ratio of 0.1473 ($\hat{R}_w = 0.1473$). Multiplying this weight ratio by the total weight produces an estimate of weight in the lower 7 m (23 ft) of continuous crown: 0.1473 x 393 kg = 58 kg (128 lb). The second weight ratio is computed from a length ratio of (7+10)/30 = 0.57. Using $R_L = 0.57$ provides an estimate of $\hat{R}_w = 0.62$. The estimated weight for the lower 17 m (56 ft) of continuous crown is 0.62 x 393 kg = 244 kg (538 lb). The difference in these two weights is the estimated weight of the 10-m (32.8-ft) crown section of interest; that is, 244 kg - 58 kg = 186 kg (410 lb). So the estimated dry weight of the 10-m (32.8-ft) crown section beginning 7 m (23 ft) from the bottom of the continuous crown is 186 kg (410 lb). This is dry weight which must be converted to green weight. For this example we used a moisture content of 90 percent. Green weight is then (1+0.9)(186) = 353 kg (778 lb).

When trees are felled, some limbs and parts of limbs will be broken from the bole. As discussed earlier, the loss in weight from breakage can be substantial. In applying these prediction methods, a visual estimate should be made of the percentage of branch or branches missing. These percentages are used to adjust estimated weights.

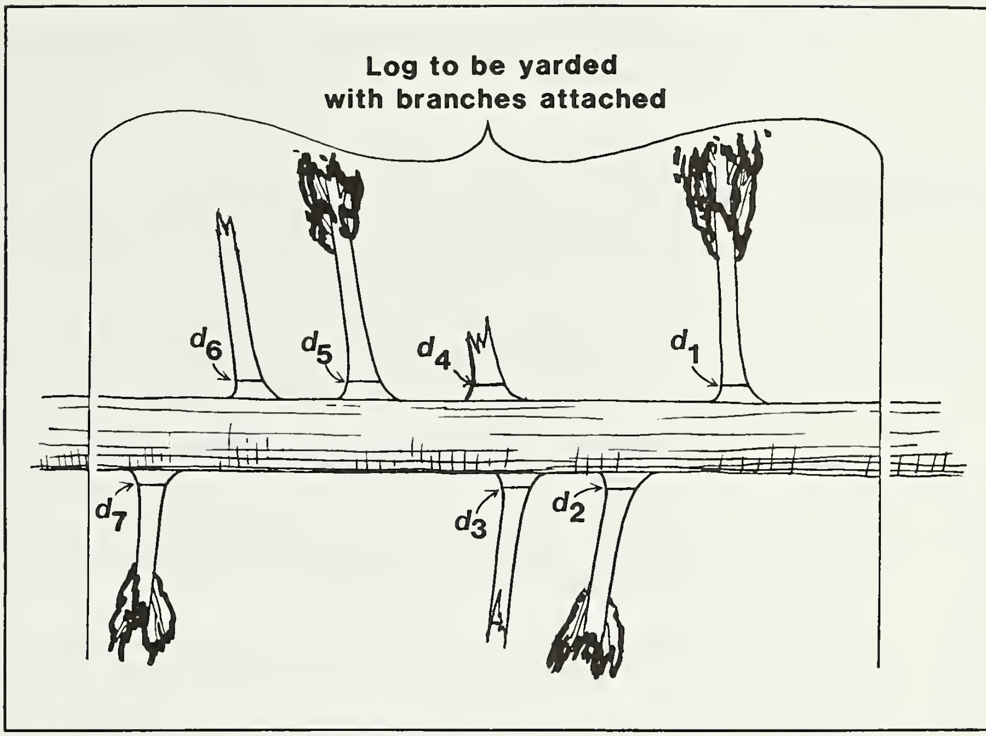

Figure 5.—Use of the branch method requires a measurement of basal diameter of all branches attached to the section of interest after the tree is felled.

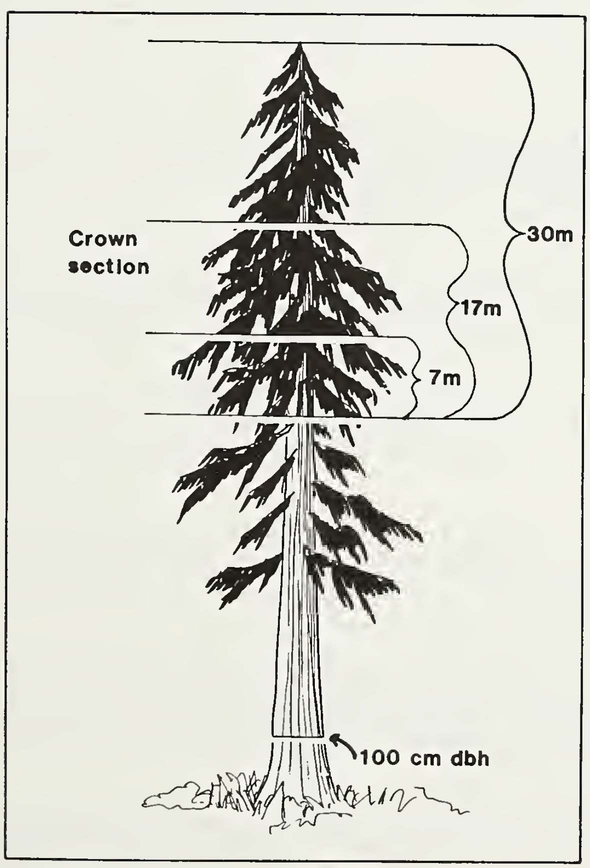

Figure 6.—Measurements needed to apply the ratio method.

Metric and English Units of Measure

When you know:	Multiply by:		To find:
Centimeters	0.394		Inches
Meters	3.281		Feet
Kilograms	2.205		Pounds
Hectares	2.471		Acres
Celsius	1.8	then add 32	Fahrenheit

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Equations were developed for predicting weight of continuous live crown, total live crown, dead crown, any segment of live crown, and individual branches for old-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) trees. A branch method and a ratio method were developed for estimating the weight of crown segments. Equations were based on data from 32 Douglas-fir and 29 western hemlock trees from the Gifford Pinchot National Forest in southwestern Washington. An additional 49 Douglas-fir and 50 western hemlock were selected for validating the models.

For predicting weight of a segment of crown, the branch method was less biased and more accurate than the ratio method. The branch method is recommended for felled trees because it more easily accommodates the large amount of breakage in the crown of felled old-growth trees.

Keywords: Crown weights, estimates, moisture content (wood), old-growth stands, Douglas-fir, western hemlock.

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